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Seismic responses of arch dams due to non-uniform ground motions

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Abstract In the present paper, spatially variation input effects on seismic responses of arch dams have been studied. Recorded ground accelerations at the dam foundation interface of Pacoima dam during January 13, 2001 were used for the purpose of this investigation. A numerical finite element model was developed for dynamic analysis of the dam reservoir system. The modified version of NSAD-DRI finite element program was used for the analysis and the ground acceleration time histories were interpolated at all dam foundation interface nodal points. Total and pseudo static displacements as well as developed stresses due to uniform and non uniform excitations are obtained. The results reveal that multiple support excitations can have profound effects on the dam responses.

1. Introduction

Seismic analysis of dams is usually performed based on the assumption that the earthquake input motions at the base are uniform and thus the entire contact region of the dam and foundation is subjected to the same ground accelerations [1,2]. In large structures such as dams, long span bridges and piping systems, due to long structure foundation interface, uniform seismic excitation assumption is not reasonable and can lead to inaccurate results [2,3].

Recorded motions have shown that due to the finite speed of earthquake waves propagation, the ground motion is delayed at the abutment compared to the base of the dam [2,4]. The wave propagation speed can vary from 200 to 4000 m/s [3] depending on the geological condition of the dam site. Topographic amplification at different contact points of the dam foundation interface is expected as a result of various sources and path effects such as mechanical factors of the seismic source, geological non homogeneity and wave reflection and refraction across interfaces of layers along the wave path [5]. Similar ground motion amplification is reported at the bases of long piping systems [6].

In recent years, few dams are equipped with accelerometers arrays. The accelerometers have been installed at different locations of the dam foundation interface and have recorded several earthquake ground motions [7]. The recorded acceleration time histories at Mauvoisin [7], Pacoima [2] and Karun III dams [8] have provided valuable data for evaluation of finite element analysis and dam responses under multiple support excitations. Hall and Alves have studied the topographic amplification and time delay of ground motions at Pacoima dam [9]. The finite element analysis revealed that if the motion recorded at the base of the dam is used as uniform input, the responses will be less severe compared to the non-uniform input. Water compressibility was ignored in their study and 4-node shell elements were used for modelling of the dam body. Chopra and Wang investigated Mauvoisin and Pacoima dams responses subjected to non-uniform ground motions [10]. Their analyses are carried out by EACD-2008 software which is developed in frequency domain and can be used just for linear analysis. Shell elements were utilized for finite element modelling of the dam body [11].

In this study, the seismic responses of Pacoima dam subjected to the non-uniform support excitations recorded during January 13, 2001 are investigated.

2. Multiple support excitation formulation

Multiple support excitations theory has been the subject of many researches for the past decade [12]. The earthquake ground motions at all support nodes of finite element model of the structural system are considered as the input data and should be specified.

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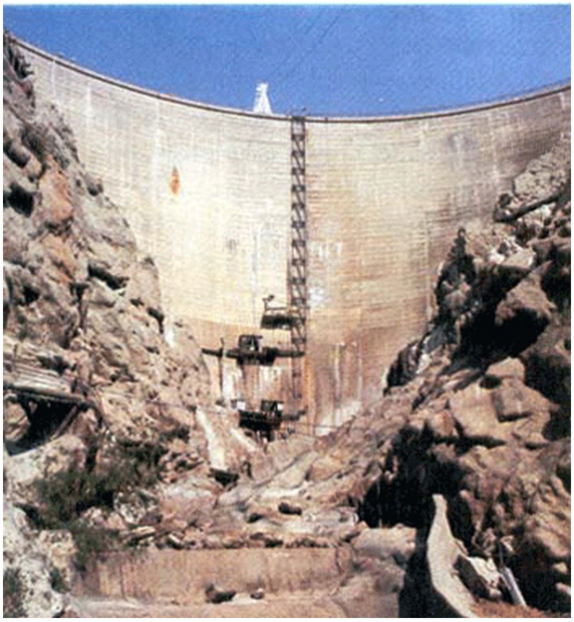

Figure 1: View of Pacoima dam.

The structure degrees of freedom can be divided into two groups, the support degrees of freedom, $\mathbf{u}_g$, and the unsupported degrees of freedom, $\mathbf{u}^t$. The dynamic equilibrium for all degrees of freedom can be written in the partitioned form as:

$$\begin{bmatrix} \mathbf{m} & \mathbf{0} \\ \mathbf{0} & \mathbf{m_{gg}} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{u}}^\mathbf{t} \\ \ddot{\mathbf{u}}_\mathbf{g} \end{Bmatrix} + \begin{bmatrix} \mathbf{c} & \mathbf{c_g} \\ \mathbf{c_g^T} & \mathbf{c_{gg}} \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{u}}^\mathbf{t} \\ \dot{\mathbf{u}}_\mathbf{g} \end{Bmatrix} + \begin{bmatrix} \mathbf{k} & \mathbf{k_g} \\ \mathbf{k_g^T} & \mathbf{k_{gg}} \end{bmatrix} \begin{Bmatrix} \mathbf{u}^\mathbf{t} \\ \mathbf{u_g} \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ \mathbf{P_g(t)} \end{Bmatrix}, \tag{1}$$

where $\mathbf{m}$, $\mathbf{m}_{gg}$, $\mathbf{c}$, $\mathbf{c}_{gg}$ and $\mathbf{k}$, $\mathbf{k}_{gg}$ are mass, damping and stiffness matrices corresponding to unsupported and supported degrees of freedom respectively, and $\mathbf{c}_g$ and $\mathbf{k}_g$ are coupling damping and stiffness matrices. $\mathbf{u}_g$, $\dot{\mathbf{u}}_g$ and $\ddot{\mathbf{u}}_g$ are input ground motions at the support degrees of freedom which must be specified. The displacements can be separated into pseudo static and dynamic displacement as:

$$\begin{Bmatrix} \mathbf{u}^t \\ \mathbf{u}_g \end{Bmatrix} = \begin{Bmatrix} \mathbf{u}^s \\ \mathbf{u}_g \end{Bmatrix} + \begin{Bmatrix} \mathbf{u} \\ \mathbf{0} \end{Bmatrix}, \tag{2}$$

where, $\mathbf{u}^s$ is the displacement vector of unsupported degrees of freedom due to the static application of the prescribed support displacement at each time instant. By eliminating the time dependent terms of Eq. (1), the pseudo static displacement can be computed as:

$$\mathbf{u}^s = \iota \mathbf{u}_g, \qquad \iota = -\mathbf{k}^{-1}\mathbf{k}_g. \tag{3}$$

Substituting Eqs. (2) and (3) into the first row of the matrix in Eq. (1) results in:

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{k}\mathbf{u} = -(\mathbf{m}\iota\ddot{\mathbf{u}}_g) - (\mathbf{c}\dot{\mathbf{u}}^s + \mathbf{c}_g\dot{\mathbf{u}}_g) - (\mathbf{k}\mathbf{u}^s + \mathbf{k}_g\mathbf{u}_g). \tag{4}$$

The third term in the right hand side of the above equation is zero from Eq. (3). The contribution of damping term is negligible compared to the first term and can be disregarded. For stiffness proportional damping, the corresponding term will be zero and Eq. (4) can be simplified as:

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{k}\mathbf{u} = -\mathbf{m}\iota\ddot{\mathbf{u}}_g. \tag{5}$$

This equation is similar to the standard governing equation for a system under uniform excitations and the recorded acceleration values are merely used in the analysis. For uniform base excitations, the pseudo static displacement of the structure will be the same as the ground motion input and no stress will be developed in the dam body. If the non-uniform accelerations are exerted at the support nodes, the pseudo static displacement can cause the stresses to be developed.

3. Recorded ground motions on Pacoima dam

Pacoima dam is a double curved concrete arch dam. The height and the crest length of the dam are 113 and 180 m, respectively. Figure 1 portrays a view of Pacoima dam.

An array of 17 accelerometers has been installed on Pacoima dam to investigate the dam responses and the characteristics of earthquake ground motions at the dam foundation interface. As it is illustrated in Figure 2, channels 9 to 15 have been located at the dam foundation interface and designed to record all three components of any probable ground accelerations. Channels 1 to 8 have been installed within the dam body.

This array of accelerometers has recorded the 1994 Northridge earthquake with magnitude of 6.7. Another earthquake with the magnitude of 4.3 has been recorded on January 13, 2001. Figure 3 displays the stream component of this ground motions at various stations. The accelerographs and their corresponding PGAs prove the non-uniform nature of ground motions at the dam foundation interface during earthquakes. For instance, the PGA varies from 13 cm/s^2 at the base to 34 and 43 cm/s^2 at the left and right abutments, respectively.

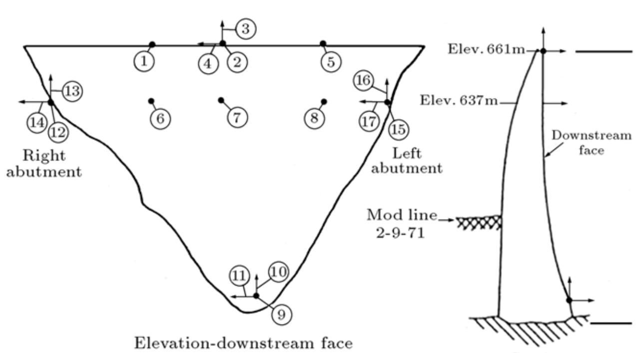

Figure 2: Location of accelerometer installed on Pacoima dam [5].

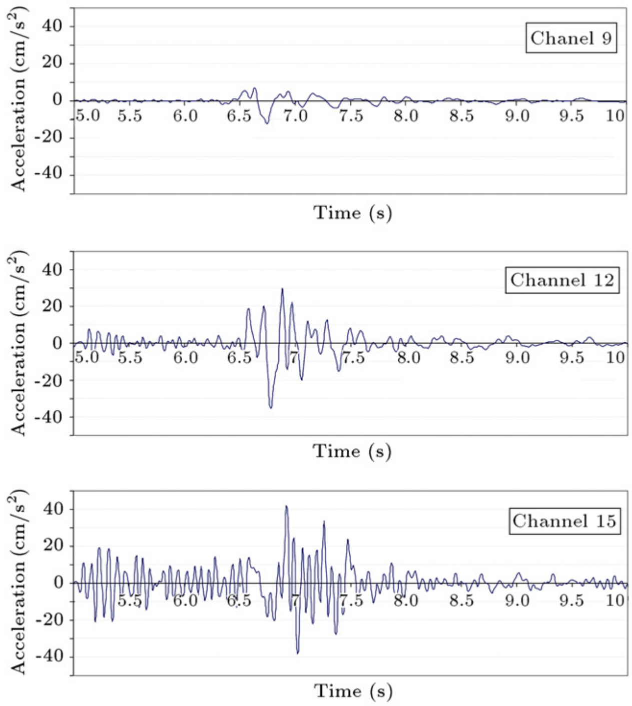

Figure 3: Stream component of January 13, 2001 earthquake at base, left and right abutments.

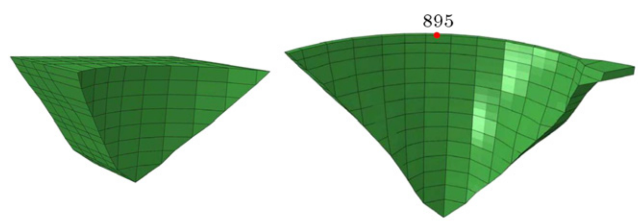

Figure 4: Finite element model of Pacoima dam body and its reservoir.

4. Finite element model of Pacoima dam

Figure 4 shows the provided finite element model of Pacoima dam. One hundred and ten 20-node solid brick elements including 908 nodes are employed to model the dam body. The reservoir elevation at the time of the earthquake occurrence was 41 m below the crest level. For modelling of the reservoir, 392 of 8-node fluid elements are used. The reservoir length is taken as twice of its depth.

The modulus of elasticity for mass concrete is 21.9 GPa and its density and Poisson ratio are taken to be 22.3 KN/m^3 and 0.2, respectively. The density of water is 1000 kg/m^3.

The NSAD-DRI program was used to study the seismic response of Pacoima dam. This program was developed to consider the non-uniform nature of ground motions as incorporated in this study. In this program, the staggered method is used for dam reservoir interaction; water compressibility is taken into account. Although linear and nonlinear analysis based on the smeared crack model can be conducted by NSAD-DRI, this study is just limited to the linear behavior of the dam reservoir system [13].

As mentioned earlier, the ground acceleration time histories at all finite element nodes at the dam foundation interface are required and should be specified. However, due to the extended dam foundation contact region and the limited number of installed accelerometers, the input ground motions at all finite element nodal points are not available and should be estimated. These input ground motions were generated by interpolation and extrapolation of the acceleration time histories of the base and the abutment stations. Ground motions are assumed to be uniform across the thickness.

The ground acceleration time histories employed in this study have been recorded at the dam foundation interface; consequently, the dam foundation interaction effects are included. Therefore, in the finite element model, the foundation was excluded.

5. Results and discussion

Figure 5 presents the computed and recorded displacements of crest in stream, cross stream and vertical directions. In spite of several differences at peak values, the results reveal that the trend of the computed displacements is in a reasonable agreement with the recorded motions at this station. The differences are attributed to the limited number of installed accelerometers at dam foundation interfaces. On the other hand, the considered displacements are computed at node 895 which is not located exactly at accelerometer position.

The total and pseudo static displacements at crest for stream, cross stream and vertical components are presented in Figure 6 to investigate the influence of pseudo static displacement on the total responses. As it is evident, the pseudo static

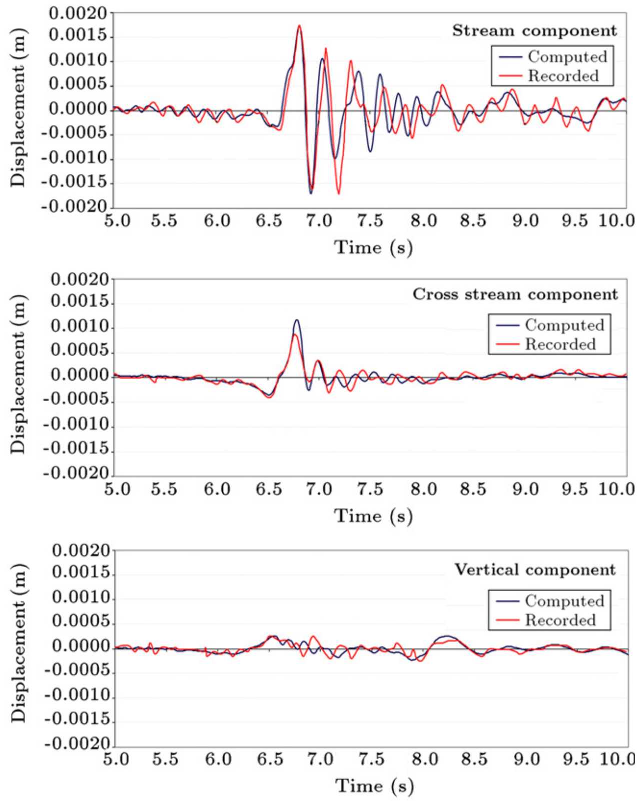

Figure 5: Recorded and computed displacements in the stream, cross stream and vertical directions at crest (node 895).

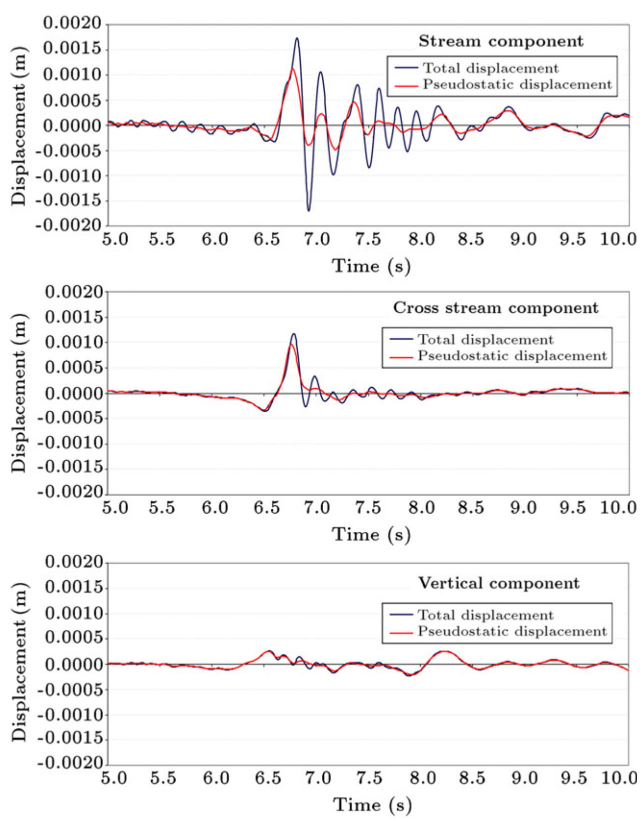

Figure 6: Total and pseudo static displacements in the stream, cross stream and vertical directions at crest (node 895).

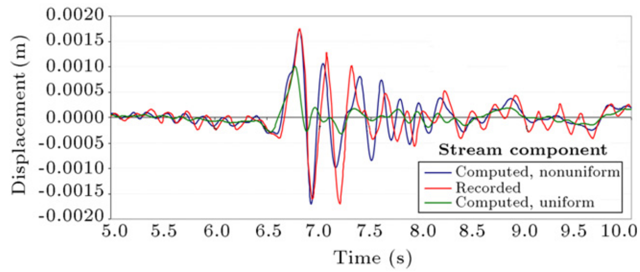

Figure 7: Recorded and computed displacements subjected to uniform and non-uniform excitations in the stream direction at crest (node 895). (a) Maximum tensile arch stress for multiple support excitations; and (b) maximum tensile arch stress for uniform support excitations.

(a) Maximum tensile arch stress for multiple support excitations.

(b) Maximum tensile arch stress for uniform support excitations.

Figure 8: Maximum tensile arch stress (MPa) at upstream face for uniform and non-uniform excitations.

displacement is the major part of total displacement for vertical and cross stream components; however, this ratio is not such dominant for stream components. This ratio for stream, cross stream and vertical directions is about 65%, 85% and 100%, respectively.

The crest displacement and stress distribution due to uniform and non-uniform excitations are presented in Figures 7 and 8 to study the influence of multiple support excitations on the dam responses. The acceleration time histories of the base station (channels 9–11) are used for this uniform analysis. The obtained results prove that the responses of the system to the spatially varying excitations are in a more satisfactory agreement with the recorded crest displacement. The analysis with uniform excitations underestimates the displacement up to 58% for this analysis.

The maximum tensile arch stress on upstream face of the dam is shown in Figure 8 for uniform and non-uniform excitations. Although the overall patterns of stress are similar, their magnitudes are different. The multiple support excitations results in higher stresses on the dam body. This increasing trend can be due to the pseudo static effect on the dam responses as well as the less PGA of the applied accelerations in the uniform analysis. As mentioned earlier, the pseudo static part of the total displacement is the same for the whole model in the case of uniform excitations; therefore, no stresses will be developed on the dam body.

6. Conclusions

Although the ground accelerations recorded at Pacoima dam on January 13, 2001 are low intensity earthquakes, they are extremely valuable to study the spatial variations of earthquake waves at the dam foundation interface.

The responses of Pacoima dam subjected to January 13, 2001 earthquake were investigated by modified version of NSAD-DRI program. The results have indicated that the computed crest displacements based on spatially varying earthquake assumption are in an acceptable agreement with the recorded displacements of the dam. Generally, applying the base motions as the uniform excitations, underestimate the crest displacements and developed stresses in the dam body. Although the overall trend of the computed and recorded responses are well, there are several differences in the peak magnitudes.

Studying the recorded motion on the next probable earthquakes on such well-instrumented dams can help us to calibrate finite element models and have a more accurate interpretation on seismic behaviour of arch dams.

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References

[1] Nowak, S. and Hall, J. "Arch dam response to non-uniform seismic input", *J. Eng. Mech.*, 116(1), pp. 125–139 (1990).

[2] Alves, S.W. "Nonlinear analysis of Pacoima dam with spatially non-uniform ground motion", *Earthquake Engineering Research Laboratory*, California Institute of Technology, Report No. EERL 2004-11, Caltech, Pasadena, Calif (2004).

[3] Dumanoglu, A.A., Severn, R.T. and Taylor, C.A. "Effect of Asynchronous input on the response of dams", *Proceedings 8th World Conf. on Earthquake Engineering*, 6, San Francisco, pp. 127–134 (1984).
[4] Maheri, M.R. and Ghaffarzadeh, H. "Asynchronous and non-uniform support excitation analysis of large structures", *JSEE*, 4(2&3), (2002).
[5] Ramadan, O. and Novak, M. "Coherency functions for spatially correlated seismic ground motions", Geotechnical Research Center, Faculty of Engineering Science, The University of Western Ontario. Report No. GEOT-9-93 (1993).
[6] Ramadan, O. and Novak, M. "Dam response to spatially variable seismic ground motions", Geotechnical Research Center, Faculty of Engineering Science, The University of Western Ontario. Report GEOT-14-92 (1992).
[7] Proulx, J., Darbre, G. and Kamileris, N. "A comparison of recorded and computed earthquake motions of large concrete dams", *First European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland, Paper No. 627 (2006).
[8] Sohrabi Gilani, M. and Ghaemian, M. "Seismic response of arch dam subjected to multiple support excitations", 14 ECEE, No. 706, Macedonia (2010).
[9] Hall, J.F. and Alves, S.W. "Generation of spatially non-uniform ground motion for nonlinear analysis of a concrete arch dam", *Earthq. Eng. Struct. Dyn.*, 35, pp. 1339–1357 (2006).
[10] Chopra, A.K. and Wang, J. "Earthquake response of arch dams to spatially-varying ground motion", *Earthq. Eng. Struct. Dyn.*, 39, pp. 887–906 (2009).
[11] Chopra, A.K. and Wang, J. "Analysis and response of concrete arch dams including dam water-foundation rock interaction to spatially-varying ground motions", Report No. UCB/EERC-2008/03, Earthquake Engineering Research Center, University of California, Berkeley, Calif., 124 pp (2008).
[12] Chopra, A.K., *Dynamics of Structures: Theory and Applications to Earthquake Engineering*, 3rd Edn., Prentice Hall, Upper Saddle River, New Jersey (2007).
[13] Mirzabozorg, H. "Non-linear 3-D seismic analysis of concrete arch dams with dam-reservoir interaction", Ph.D. Thesis, Sharif University of Technology, Tehran, Iran (2004).

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